On dark matter

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In this article, I shall propose an enlightening view on the origin of dark matter abundance, in which I introduce a neutral primordial field, which is a new field beyond the standard model, the mass of the primordial field is confined in the vicinity of neutrino mass (or 1-2 orders of magnitude different from the neutrino mass). All the standard model elementary particles are produced spontaneously from this field in the Big Bang epoch of the universe and then these produced elementary particles decayed or annihilated in the well-known standard model interactions. The relic of the primordial field appears in a form of vacuum energy can not only give naturally the correct abundance of dark matter in the present universe, but provide a natural solution to the cosmological constant problem as well. We find that the conventional methods of detecting dark matter either fail or have great difficulties to detect the remaining vacuum energy of the primordial field, and how to confirm the existence of the remaining energy of the universe's original energy in experiment is still an open problem.

I. INTRODUCTION

Einstein's discovery of general relativity enabled us for the first time to understand the universe quantitatively and accurately. Owing to the developments, both theoretical and observational, in the last two decades of the twentieth century, we have enormous undoubted and convincing evidences which point to the existence of dark matter in the universe. The most convincing and direct evidence for the existence of dark matter on galactic scales come from the observations of the velocity distribution of galaxies. Apart from the rotation curves of galaxies, the hot gas which produce bremsstrahlung emission of X-rays distributed throughout the clusters of galaxies and gravitational lensing studies of distant galaxies also provide strong evidence for the predominance of dark matter in galaxies. Furthermore, the analysis of the cosmic microwave background provide us the information that dark matter is about five times more abundant than baryonic matter, accounting for about 85% of the total matter in the universe.

Although many experimental attempts have been done to reveal the nature of dark matter, what on earth is dark matter is still remain mysterious after almost a century since it was initially proposed by Zwicky [1]. Only lower and lower limits for their masses are set with these experiments. The searches for weakly interacting massive particles are still null results when the latest upper limit on the WIMP-nucleon spin-independent elastic scattering cross section reaches the level of $10^{-47}\ \mathrm{cm}^2$ [2], which is only about two orders of magnitude higher than the neutrino-induced background. Axion, which arises from attempts to explain why the strong interaction obeys the CP symmetry, is another popular candidate for dark matter. The major challenges for the detection of axions in experiments are the particle's mass and coupling constant are unknown, the predicted masses of axions range from $1\ \mu\mathrm{eV}$ to $1\ \mathrm{eV}$. The continuing null results from searches for standard axions are narrowing the potential mass range for hypothetical dark matter axions bit by bit. Since the contradictory results from different experiments for the searches of sterile neutrino, one of the proposed dark matter candidates, the existence of sterile neutrino is still a question.

Another unresolved problem in cosmology is the cosmological constant problem [3]: a huge discrepancy does exist between the theoretical value of vacuum energy density and the critical density. Although there are many attempts to solve the cosmological constant problem, including in the framework of supersymmetry or quantum gravity and quantum cosmology, each approach has its own defect and none of them gives a satisfactory solution.

In conventional viewpoint, dark matter puzzle and cosmological constant problem are two independent problems. However, in this article, I shall propose a new theory of dark matter, in which I introduce a neutral primordial field, which is a new field beyond the standard model. All the standard model elementary particles are produced spontaneously from this field in the Big Bang epoch of the universe and the relic of the primordial field appears in a form of vacuum energy can not only give naturally the correct abundance of dark matter in the present universe, but provide a natural solution to the cosmological constant problem as well. The details of the new theory of dark matter and various supporting arguments for the new theory will be discussed fully in Sec. II, and in Sec. III, we explain why the conventional methods for dark matter detection either fail or have great difficulties to detect the dark matter.

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II. THE NEW THEORY ON THE ORIGIN OF DARK MATTER ABUNDANCE

In quantum field theory, for each model of a quantum field there is a zero-point energy $\frac{1}{2}\sqrt{k^2+m^2}$, so the energy density of the quantum vacuum is given by [4]

$$\rho_{\rm vac} = \frac{1}{2}\sum_{\rm fields} g_i \int_0^\infty \sqrt{k^2+m^2}\frac{d^3k}{(2\pi)^3} \simeq \sum_{\rm fields}\frac{g_i k_{\rm max}^4}{16\pi^2}, \tag{1}$$

where g_i is the degrees of freedom of the field and the sum runs over all quantum fields(e.g., quarks, leptons, gauge fields, etc.). $k_{\rm max}$ is an imposed momentum cutoff.

On the other hand, the energy density of empty space must satisfy the following observational bound

$$\rho_{\rm vac} < \rho_{cr} \sim 10^{-11}{\rm eV}^4. \tag{2}$$

The trouble is that the energy density of the vacuum is likely to be enormously larger than ρ_{cr}. To illustrate the magnitude of the problem, supposing the energy density contributed by just one scalar field with the condition $m \ll k_{\rm max}$. Taking the cutoff to be the Plank scale, where one expect quantum field theory in a classical space-time metric to break down, the vacuum energy density will exceed the critical density ρ_{cr} by 120 orders of magnitude! If we taking the cutoff to be electroweak symmetry breaking scale $M_{\rm EW} \sim 200{\rm GeV}$ or QCD scale $\Lambda_{\rm QCD}$, a huge discrepancy between the theoretical value of vacuum energy density and critical density does still exist, which is known as the cosmological constant problem [3].

There are many attempts to solve the cosmological constant problem. Supersymmetry, a hypothetical symmetry between bosons and fermions, appears to provide only partial help [4]. Zumino pointed out that supersymmetry, if unbroken, imply a vanishing vacuum energy [5]. However, supersymmetry has to be broken in the real world and this destroy the miraculous cancellation of the various terms participating the vacuum energy. If we taking the momentum cutoff at the scale of supersymmetry spontaneously broken($\sim 1{\rm TeV}$), this lead to a discrepancy of 60(as opposed to 120) orders of magnitude with observations. Another solution is based on quantum gravity and quantum cosmology [6–8]. However, this approach suffer from various limitations among which is the fact that the path integral is not properly defined and that probabilities are not positive definite [9]. Anthropic principle is also one approach to the cosmological constant problem which involves the idea about the vacuum energy is a random variable that can take on different values in different disconnected regions of the universe. Because large vacuum energy would forbid the formation of galaxies, the reason for why the vacuum energy of the universe is so tiny is just that we could not exist in a region with large $\rho_{\rm vac}$ [10]. There are other approaches to the cosmological constant problem, each approach has its own defect and none of them gives a satisfactory solution. For review, see Refs. [3, 9, 11].

A. The new theory on the origin of dark matter abundance

The fact that all attempts to estimate the size of vacuum energy are at best orders of magnitude too large, which motivates us to must think outside the box. In conventional viewpoint, vacuum energy is mathematically equivalent to a cosmological constant, if we give up the old idea, one way out of both the cosmological constant problem and dark matter puzzle appears. First, we provide a definition of the stability of vacuum state and two basic postulates about the beginning of the universe.

Definition: If a vacuum state, real particle-antiparticle pairs can not be created spontaneously from it, we call it stable vacuum state; otherwise, it is unstable vacuum.

The moment after the Big Bang is the time when all kinds of particles are created. This process continues to produce all kinds of particles that fill the universe, including the basic particles that make up atoms, neutrinos and possible dark matter particles, and finally form the familiar matter. It is very complicated to describe the creation process of particles in detail, but thanks to Einstein's mass energy relation $E = mc^2$, which describes the equivalence of mass and energy. So at the beginning of the universe, particles were produced by the following process [12]

$$Energy \to particle + antiparticle. \tag{3}$$

It must be emphasized that this process can only occur if the energy provided exceeds the total mass of the final particle and antiparticle to be produced.

The question is, before the creation of particles, what was the initial form of energy in the universe? It is generally believed that the initial pure energy of the universe was photons, if it was, formula(3) becomes $\gamma+\gamma \to particle + antiparticle$. Of course, if photon's energy is high enough, it is always possible to create any type of particle antiparticle pair in the process of photon collision(for example, $\gamma+\gamma \to e^+ + e^-$, $\gamma+\gamma \to q+\bar{q}$, etc.). However, the generation of particles from photon collisions is an electromagnetic interaction. If the original pure energy form of the universe was photons, it is contrary to the well-known electro-weak unified theory that electromagnetic interaction exists only after electro-weak symmetry breaking, so the original pure energy of the universe cannot be photons. What would it be? We will give an answer to this question in Postulate I below.

When a particle is produced in the universe, no matter what kind of particle it is, its number density is inevitably diluted with the expansion of the universe. When the number density of particles in the universe drops to a critical value, the average distance between particles is too large, the interaction between them can not be carried out effectively, and the number of such particles is gradually fixed [12], which is the thermal decoupling mechanism of the origin of dark matter abundance. The relic abundance of dark matter can be described and calculated by the standard Boltzmann equation. If dark matter is really a kind of particle and produced by formula(3), there is no problem about the thermal decoupling mechanism of the origin of dark matter abundance. However, there is another possibility that dark matter is not a particle. We can ask another question: is it true that 100% of the original energy of the universe is converted into particles without any surplus? Along this line of thought, a new theory on the origin of dark matter abundance came into being.

The whole universe must be in an unstable vacuum state in the beginning, or in the pre-big-bang epoch, then big bang occurred and all elementary particles in the standard model were created spontaneously from it described by formula(3).

Postulate I: At the first moment of the beginning of the universe, before the production of elementary particles, there is only energy, no particles. In addition to a very small cosmological constant, all energy of the universe were stored in the form of vacuum energy of a neutral primordial field.

$$\rho(t=0) = g\int_0^{k_{\max}(t=0)} \frac{d^3k}{(2\pi)^3}\frac{1}{2}\sqrt{k^2+m^2} + \rho_\Lambda, \tag{4}$$

where the factor $g = 2s+1$ accounts for the degree of freedom of the primordial field.

Here we use $t = 0$ mean the moment of the beginning of the universe, or the beginning of time. In the first term of the right side of Eq.(4), we introduce a new field, the primordial field, which is beyond the standard model. The precise value of the momentum cutoff at $t = 0$ moment is not known, this is in fact not important. The most important thing is that, as I shall show below, this vacuum state is unstable regardless of the quantity $k_{\max}(t = 0)$ and all elementary particles in the standard model would be created spontaneously from it, and its energy density varies with time, while the second term ρ_Λ with energy density which remains constant throughout the history of the universe.

The primordial field may be scalar field, spin-1/2 field, vector field or other fields. Different scalar field models have been fully studied in related literatures, and the simplest one is to add another term to the Lagrangian of the standard model [13]

$$L_S = \partial^\mu S\partial_\mu S - m^2 S^\dagger S - \lambda_S S^\dagger S H^\dagger H. \tag{5}$$

This model has a global U(1) symmetry which guarantees the stability of the S scalar by eliminating the interaction terms involving odd powers of S and $S^\dagger$ which lead to S decay. If dark matter is a vector particle, the popular model is an extension of the SM by an additional $U(1)_X$ gauge symmetry and a complex scalar field $\Phi = (\phi_r + i\phi_i)/\sqrt{2}$, whose vacuum expectation value generates a mass of this U(1)'s vector field. The Lagrangian of the scalars and the new vector boson is [14]

$$L = D_\mu\Phi D^\mu\Phi - \frac{V_{\mu\nu}V^{\mu\nu}}{4} - V(\Phi, H), \tag{6}$$

where $V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu$, $D_\mu = \partial_\mu - ig_V V_\mu$ and

$$V(\Phi, H) = -\mu_\phi^2|\Phi|^2 - \mu^2|H|^2 + \lambda_\phi|\Phi|^4 + \lambda|H|^4 + \lambda_{H\phi}|\Phi|^2|H|^2. \tag{7}$$

Eqs. (5) and (6) are examples of specific dark matter model. It will be shown that our discussions and conclusion have nothing to do with the specific dark matter model.

Postulate II: each mode(mode k) of this neutral primordial field is stale and has a zero-point energy $\frac{1}{2}\sqrt{k^2+m^2}$.

The accurate value of the primordial field's mass is not known, but it could be expected that its mass is very light, so each zero-point energy mode of this primordial field(with a energy $\frac{1}{2}\sqrt{k^2+m^2}$) is neutral, stable and nonbaryonic, and thus satisfies basic requirements for dark matter.

Although each mode k(with a energy $\frac{1}{2}\sqrt{k^2+m^2}$) is stable, two modes, k_1(with a energy $\frac{1}{2}\sqrt{k_1^2+m^2}$) and k_2(with a energy $\frac{1}{2}\sqrt{k_2^2+m^2}$), may annihilate into a pair of standard model elementary particles when they collide, as described by formula(3)

$$\begin{aligned}
&k_1 + k_2 \to f\bar{f}, \quad && if \quad \frac{1}{2}\sqrt{k_1^2+m^2} + \frac{1}{2}\sqrt{k_2^2+m^2} \geq 2m_f,\\
&k_1 + k_2 \to W^+W^-, \quad && if \quad \frac{1}{2}\sqrt{k_1^2+m^2} + \frac{1}{2}\sqrt{k_2^2+m^2} \geq 2m_W,\\
&k_1 + k_2 \to Z^0Z^0, \quad && if \quad \frac{1}{2}\sqrt{k_1^2+m^2} + \frac{1}{2}\sqrt{k_2^2+m^2} \geq 2m_Z,\\
&k_1 + k_2 \to H^0H^0, \quad && if \quad \frac{1}{2}\sqrt{k_1^2+m^2} + \frac{1}{2}\sqrt{k_2^2+m^2} \geq 2m_H,
\end{aligned} \tag{8}$$

which explains the fact that the standard model elementary particles are produced from vacuum state in the Big Bang epoch of the universe. The process $k_1 + k_2 \rightarrow \gamma + \gamma$(just like $\nu + \bar{\nu} \rightarrow \gamma + \gamma$) is forbidden or strongly suppressed because of the well-known fact that dark matter is not involved in electromagnetic interaction.

One may wonder whether vacuum energy can annihilate into elementary particles, as suggested in Eq.(8). By definition, vacuum describes the lowest possible energy state in QFT, this is indeed the case. Each mode k, whose minimum energy $\frac{1}{2}\sqrt{k^2+m^2}$ is indeed less than a particle's energy $\sqrt{k^2+m^2}$, this means that each mode k in vacuum energy is stable and cannot decay. However, a particle that cannot decay spontaneously does not mean that two particles cannot annihilate. Just like a photon is stable and cannot decay into any particles, but two photons can annihilate(for example $\gamma + \gamma \rightarrow e^+ + e^-$), the same is true for each mode k in vacuum energy.

It must be emphasized that we discuss the occurrence of the reaction Eq. (8) from the law of conservation of energy and mass energy relation, as long as the energy condition is satisfied just like in formula(3), reaction Eq. (8) will certainly occur. As for the specific value of the annihilation cross section and how the SM particles are produced from this new field, which are obviously model dependent(for example, in Ref. [13], the author calculated the annihilation cross sections of a pair of dark matter annihilated into a pair of standard model particles in a scalar dark matter model), is not important. Then these produced elementary particles decayed or annihilated in the well-known standard model interactions and after the Big Bang Nucleosynthesis, only photon, neutrino and light elements are left. The energy density of the universe described by Eq.(4) becomes correspondingly

$$\rho(t) = \rho_\gamma(t) + \rho_\nu(t) + \rho_b(t) + g\int_0^{k_{\max}(t)} \frac{d^3k}{(2\pi)^3}\frac{1}{2}\sqrt{k^2+m^2} + \rho_\Lambda. \tag{9}$$

The primordial field's vacuum energy density(the first term on the right side of Eq.(4)) decreases with time for two reasons: the elementary particles in the standard model are created spontaneously from it and the universe expands, and correspondingly so does the maximum momentum $k_{\max}$, which is determined by the vacuum energy density via the following theorem

Theorem I: The vacuum energy density of the primordial field is given by

$$\rho_{\text{vac}}(t) = g\int_0^{k_{\max}(t)} \frac{d^3k}{(2\pi)^3}\frac{1}{2}\sqrt{k^2+m^2} = \frac{gk^4_{\max}(t)}{16\pi^2} f\left(\frac{m}{k_{\max}(t)}\right), \tag{10}$$

where $f(x) = \sqrt{1+x^2}(1+\frac{1}{2}x^2) - \frac{1}{2}x^4\ln(\frac{1}{x}+\frac{1}{x}\sqrt{1+x^2})$ and $k_{\max}(t)$ is momentum cutoff.

When $\frac{1}{2}\sqrt{k^2_{\max}(t)+m^2} + \frac{1}{2}\sqrt{k^2_{\max}(t)+m^2} \leq 2m_\nu$, i.e. $k_{\max}(t) \leq 2m_\nu$, at that time, say $t = t_1$, even the lightest neutrinos can not be created spontaneously from the vacuum state, the vacuum became a stable vacuum. One may argue that it is at this time, say $t = t_2$, when the rate for neutrino antineutrinos created spontaneously from vacuum state becomes smaller than the expansion rate of the universe, the vacuum became a stable vacuum. The exact time t_2 is very difficult to determine because of the unknown annihilation cross section, but we must have $t_2 \leq t_1$, it does not change the fact that the vacuum was stable at the time $t = t_1$ and our following calculations will not be affected by the unknown time t_2. The detailed reason is: when the energy density of the primordial field drops to a critical value, no particles in the standard model can be produced effectively from it, and the vacuum becomes stable. Let's say that time is t_2, temperature is T_2, and cosmic scale factor is a_2. Because at the time $t = t_1$, the vacuum must be stable, so we must have $t_2 \leq t_1$. According to Theorem II(see below), we have $\rho_{\text{rvac}}(t_2)a_2^3 = \rho_{\text{rvac}}(t_1)a_1^3 = \rho_{\text{rvac}}(t_0)a_0^3$. The precise value of t_2 or T_2 and $\rho_{\text{rvac}}(t_2)$ depend on the corresponding calculations(annihilation cross section) of concrete model, which are vague and unclear, but it doesn't matter. We can calculate the value of t_1 or T_1 and $\rho_{\text{rvac}}(t_1)$, which are only depend on neutrino's mass, and thus the calculation of the relic density of dark matter $\rho_{\text{rvac}}(t_0)$ is not be affected by the unknown annihilation cross section.

Therefore, we can get a picture of the universe's evolution: in addition to a very small cosmological constant, the initial or original energy of the universe is stored in the form of vacuum energy of a neutral primordial field, because this vacuum state is unstable, the original vacuum energy is divided into two parts as the universe expands. One part had been transformed into ordinary matter or radiation through formula(8), the other part remain in the form of vacuum energy. The part left we call it remaining energy of the primordial field, its energy density evolutes via

Theorem II: $\rho_{\text{rvac}}(t)a^3(t) = Const.$

where a is the cosmic scale factor. One may argue that vacuum energy density is a constant, which does not dilute with the expansion of space. Indeed, this is a deep-rooted concept, just as people believed that all species were immutable before Darwin put forward the theory of evolution in the 19th century. In the early universe, the vacuum energy density decreased rapidly with the expansion of the universe, and then gradually slowed down. At present, the decrease of remaining vacuum energy density with the expansion of the universe must be a very, very slow process. In order to produce experimentally observable changes, it may take no less time than that required to produce a new species on Earth. Therefore, the idea that the vacuum energy density is a constant, which does not decrease with the expansion of space, is only a theoretical guess without any strict experimental confirmation. If we assume that the energy density of vacuum energy decreases with the expansion of space, it naturally explains the difficulty of cosmological constant.

When $k_{\max}$ decreased to $2m_\nu$, at that time we set $t = t_1$, $T = T_1$ and $a = a_1$, according to Eq.(10), we have

$$\begin{aligned}\rho_{\rm rvac}(t_1) &= \frac{g(2m_\nu)^4}{16\pi^2} f\left(\frac{m}{2m_\nu}\right)\\ &= \frac{gm_\nu^4}{\pi^2} f\left(\frac{m}{2m_\nu}\right).\end{aligned} \tag{11}$$

Because $\rho_{\rm rvac}(t_1)a_1^3 = \rho_{\rm rvac}(t_0)a_0^3$(*Theorem II*), here t_0 is the present time and a_0 is the present value of cosmic scale factor, then we get the present remaining vacuum energy density

$$\begin{aligned}\rho_{\rm rvac}(t_0) &= \rho_{\rm rvac}(t_1)\left(\frac{a_1}{a_0}\right)^3\\ &= \rho_{\rm rvac}(t_1)\left(\frac{T_0}{T_1}\right)^3\\ &= \frac{gm_\nu^4}{\pi^2}\left(\frac{T_0}{T_1}\right)^3 f\left(\frac{m}{2m_\nu}\right),\end{aligned} \tag{12}$$

where T_0 is the cosmic plasma temperature today, the second step is based on the formula that $a(t)T(t)$ remains constant through the evolution of the universe. Therefore the ratio of the remaining vacuum energy density today to the critical density is

$$\begin{aligned}\Omega_{\rm rvac} &\equiv \frac{\rho_{\rm rvac}(t_0)}{\rho_{cr}}\\ &= \frac{gm_\nu^4}{\pi^2\rho_{cr}}\left(\frac{T_0}{T_1}\right)^3 f\left(\frac{m}{2m_\nu}\right).\end{aligned} \tag{13}$$

Because at $T = T_1$, the lightest neutrinos can not be created spontaneously from the vacuum state, we must have $T_1 \le m_\nu$; on the other hand, approximately, $T_1 > 0.1m_\nu$(the reason will be given in the appendix). It is reasonable to take the temperature T_1 in the range of $0.1m_\nu < T_1 < m_\nu$. If we set $\Omega_{\rm rvac} = \Omega_{\rm DM} = 0.26 \pm 0.01$, then we get a limit on the lightest neutrino mass m_ν, see Table I, Table II and Table III, where we have considered three cases: the primordial field is a scalar field, a spin-1/2 field and a vector field.

TABLE I. The limit on the lightest neutrino mass m_ν(in unit of eV) from the remaining vacuum energy density today if the primordial field is a scalar field, the error comes from the function $f(\frac{m}{2m_\nu})$.

$m_\nu \backslash T_1$ / $\Omega_{\rm rvac}$	$0.1m_\nu$	$0.2m_\nu$	$0.3m_\nu$	$0.4m_\nu$	$0.5m_\nu$	$0.6m_\nu$	$0.7m_\nu$	$0.8m_\nu$	$0.9m_\nu$	m_ν
0.25	$0.007^{-0.001}_{+0.001}$	$0.059^{-0.006}_{+0.004}$	$0.200^{-0.021}_{+0.014}$	$0.474^{-0.051}_{+0.033}$	$0.925^{-0.099}_{+0.064}$	$1.599^{-0.172}_{+0.111}$	$2.539^{-0.273}_{+0.176}$	$3.790^{-0.407}_{+0.263}$	$5.396^{-0.580}_{+0.374}$	$7.402^{-0.795}_{+0.513}$
0.26	$0.008^{-0.001}_{+0.001}$	$0.062^{-0.007}_{+0.004}$	$0.208^{-0.022}_{+0.014}$	$0.493^{-0.053}_{+0.034}$	$0.962^{-0.103}_{+0.067}$	$1.663^{-0.179}_{+0.115}$	$2.640^{-0.284}_{+0.183}$	$3.941^{-0.423}_{+0.273}$	$5.612^{-0.603}_{+0.389}$	$7.698^{-0.827}_{+0.534}$
0.27	$0.008^{-0.001}_{+0.001}$	$0.064^{-0.007}_{+0.005}$	$0.216^{-0.023}_{+0.015}$	$0.512^{-0.055}_{+0.036}$	$0.999^{-0.107}_{+0.069}$	$1.727^{-0.186}_{+0.120}$	$2.742^{-0.295}_{+0.190}$	$4.093^{-0.440}_{+0.284}$	$5.827^{-0.626}_{+0.404}$	$7.994^{-0.859}_{+0.554}$

TABLE II. The limit on the lightest neutrino neutrino mass m_ν(in unit of eV) from the remaining vacuum energy density today if the primordial field is a spin-1/2 field, the error comes from the function $f(\frac{m}{2m_\nu})$.

$m_\nu \backslash T_1$ / $\Omega_{\rm rvac}$	$0.1m_\nu$	$0.2m_\nu$	$0.3m_\nu$	$0.4m_\nu$	$0.5m_\nu$	$0.6m_\nu$	$0.7m_\nu$	$0.8m_\nu$	$0.9m_\nu$	m_ν
0.25	$0.004^{-0.001}_{+0.000}$	$0.030^{-0.004}_{+0.002}$	$0.100^{-0.011}_{+0.007}$	$0.237^{-0.026}_{+0.016}$	$0.463^{-0.050}_{+0.032}$	$0.799^{-0.086}_{+0.056}$	$1.269^{-0.136}_{+0.088}$	$1.895^{-0.204}_{+0.131}$	$2.698^{-0.290}_{+0.187}$	$3.701^{-0.398}_{+0.256}$
0.26	$0.004^{-0.001}_{+0.000}$	$0.031^{-0.004}_{+0.002}$	$0.104^{-0.011}_{+0.007}$	$0.246^{-0.026}_{+0.017}$	$0.481^{-0.052}_{+0.033}$	$0.831^{-0.089}_{+0.058}$	$1.320^{-0.142}_{+0.092}$	$1.971^{-0.212}_{+0.136}$	$2.806^{-0.302}_{+0.194}$	$3.849^{-0.414}_{+0.267}$
0.27	$0.004^{-0.000}_{+0.000}$	$0.032^{-0.003}_{+0.002}$	$0.108^{-0.012}_{+0.007}$	$0.256^{-0.028}_{+0.018}$	$0.500^{-0.054}_{+0.034}$	$0.863^{-0.092}_{+0.060}$	$1.371^{-0.147}_{+0.095}$	$2.046^{-0.219}_{+0.142}$	$2.914^{-0.313}_{+0.202}$	$3.997^{-0.430}_{+0.277}$

TABLE III. The limit on the lightest neutrino mass m_ν(in unit of eV) from the remaining vacuum energy density today if the primordial field is a vector field, the error comes from the function $f(\frac{m}{2m_\nu})$.

$m_\nu \backslash T_1$ / $\Omega_{\rm rvac}$	$0.1m_\nu$	$0.2m_\nu$	$0.3m_\nu$	$0.4m_\nu$	$0.5m_\nu$	$0.6m_\nu$	$0.7m_\nu$	$0.8m_\nu$	$0.9m_\nu$	m_ν
0.25	$0.002^{-0.000}_{+0.001}$	$0.020^{-0.002}_{+0.001}$	$0.067^{-0.008}_{+0.004}$	$0.158^{-0.017}_{+0.011}$	$0.308^{-0.033}_{+0.022}$	$0.533^{-0.057}_{+0.037}$	$0.846^{-0.091}_{+0.059}$	$1.263^{-0.136}_{+0.088}$	$1.799^{-0.194}_{+0.124}$	$2.467^{-0.265}_{+0.171}$
0.26	$0.003^{-0.001}_{+0.000}$	$0.021^{-0.003}_{+0.001}$	$0.069^{-0.007}_{+0.005}$	$0.164^{-0.017}_{+0.012}$	$0.321^{-0.035}_{+0.022}$	$0.554^{-0.059}_{+0.039}$	$0.880^{-0.094}_{+0.061}$	$1.314^{-0.141}_{+0.091}$	$1.871^{-0.201}_{+0.129}$	$2.566^{-0.276}_{+0.178}$
0.27	$0.003^{-0.001}_{+0.000}$	$0.021^{-0.002}_{+0.002}$	$0.072^{-0.008}_{+0.005}$	$0.171^{-0.019}_{+0.011}$	$0.333^{-0.036}_{+0.023}$	$0.576^{-0.062}_{+0.039}$	$0.914^{-0.098}_{+0.063}$	$1.364^{-0.146}_{+0.095}$	$1.942^{-0.208}_{+0.135}$	$2.665^{-0.287}_{+0.184}$

Here we have used the input parameters [15]: $\rho_{cr} = 1.879\ h^2 \times 10^{-29}{\rm g\ cm}^{-3} = 8.098\ h^2 \times 10^{-11}{\rm eV}^4$, $h = 0.72$, $T_0 = 2.725{\rm K} = 2.348 \times 10^{-4}{\rm eV}$. For the function $f(\frac{m}{2m_\nu})$, we take the value $f(\frac{m}{2m_\nu}) = 1.08^{+0.13}_{-0.07}$, the reason will be given later in the discussion on the equation of state. From Table I, Table II and Table III, we can see that the lightest neutrino mass is in the range of

$$0.008^{-0.002}_{+0.001}\ {\rm eV} \leq m_\nu \leq 7.698^{-1.091}_{+0.850}\ {\rm eV}, \tag{14}$$

if the primordial field is a scalar field; and

$$0.004^{-0.001}_{+0.000}\ {\rm eV} \leq m_\nu \leq 3.849^{-0.546}_{+0.425}\ {\rm eV}, \tag{15}$$

if the primordial field is a spin-1/2 field; and

$$0.003^{-0.001}_{+0.000}\ {\rm eV} \leq m_\nu \leq 2.566^{-0.364}_{+0.283}\ {\rm eV}, \tag{16}$$

if the primordial field is a vector field, which are consistent with the latest upper limit on the absolute mass scale of neutrinos from Karlsruhe Tritium Neutrino experiment KATRIN [16]

$$m_\nu < 1.1\ {\rm eV}(90\%{\rm C.L.}). \tag{17}$$

and the recent upper bound for the lightest neutrino mass from data of the large scale structure of galaxies, cosmic microwave background, type Ia supernovae, and big bang nucleosynthesis [17]

$$m_\nu < 0.086\ {\rm eV}(95\%{\rm C.L.}). \tag{18}$$

Formula(14), (15) and (16) also implies that the sum of the three generation neutrinos masses $\sum m_{\nu_i} \geq 0.024^{-0.006}_{+0.003}$ eV or $\sum m_{\nu_i} \geq 0.012^{-0.003}_{+0.000}$ eV or $\sum m_{\nu_i} \geq 0.009^{-0.003}_{+0.000}$ eV, which are also consistent with the minimum sum of the masses derived from atmospheric and solar neutrino oscillation data [18, 19]

$$\sum m_{\nu_i} \geq 0.0584^{+0.0012}_{-0.0008}\ {\rm eV}. \tag{19}$$

Then, we can explain the dark matter as the relic abundance of vacuum energy of the primordial field.

(1). In the beginning, the vacuum energy density of all the standard model's quantum fields described by Eq.(1) appeared as a form of one new field's vacuum energy density(the first term on the right side of Eq.(4)), which evolves as the universe expands, and nowadays its value is $\rho_{\rm rvac}(t_0) = \Omega_{\rm DM}\rho_{cr}$, which satisfies the observational bound Eq.(2). Therefore, the new theory of dark matter could solve both the cosmological constant problem and the dark matter puzzle at the same time. The second term ρ_Λ on the right side of Eq.(4) remains constant with time, its value is $\rho_\Lambda = \Omega_\Lambda\rho_{cr} \simeq 0.69\rho_{cr}$, which accounting for cosmic acceleration. At first the first four terms on the right side of Eq.(9) dominated the energy density of the universe, then which was dominated by ρ_Λ, so the evolution of the universe must experience a process from deceleration to acceleration. Furthermore, this new theory also provides an answer to this question: where did all elementary particles in the standard model come from in the beginning? They all came from a new neutral filed, I call it the primordial field, which is beyond the standard model. The most interesting feature of this new theory of dark matter is that it could be incorporated into the standard model naturally. Although other schemes of understanding the dark matter puzzle are still possible, for example, supersymmetry or extra dimensions etc, it is obvious that the remaining vacuum energy of this primordial field is the most economical way among all these approaches to dark matter puzzle, not only because it is simple, but also it provides a solution to the cosmological constant problem as well.

(2). Collisions between galaxies clusters(containing dark matter) provide a test of the nongravitational forces acting on dark matter. If dark matter's particle interact with each other frequently and exchange little momentum, the dark matter will be decelerated by an additional drag force. In Ref. [20], using the Chandra and Hubble Space Telescope, Harvey *et al.* have observed 72 collisions, including both major and minor mergers. They were surprised to find that dark matter will pass through each other without any obstacles when galaxies clusters collide. Their result disfavoring some proposed extensions to the standard model. Dark matter's lack of deceleration was also observed in the giant "bullet cluster" collision 1E0657-558 [21]. These observations show that there is no nongravitational interactions among dark matter, its behavior is more like a kind of fluid without viscosity. Observations of Ref. [20, 21] are consistent with the new theory of dark matter. It is clear that there is no self-interaction between dark matter as it is shown in Eq.(10), since every zero-point energy mode is in its ground state, the whole behavior of vacuum energy is like a kind of superfluid which flows without any friction, and thus providing a perfect explanation to the observations of Ref. [20, 21].

(3). The whole vacuum energy has its own state equation, we rewrite Eq.(10) as [9]

$$\begin{aligned}\rho_{\text{vac}}(t) &= g\int_0^{k_{\max}(t)} \frac{d^3k}{(2\pi)^3}\frac{1}{2}\sqrt{k^2+m^2} \\ &= \frac{gk_{\max}^4(t)}{16\pi^2} f\left(\frac{m}{k_{\max(t)}}\right) \\ &= \frac{gk_{\max}^4(t)}{16\pi^2}\left(1+\frac{m^2}{k_{\max}^2(t)}+\cdots\right),\end{aligned} \tag{20}$$

where in the last expression, we have expanded the exact expression in terms of the small parameter $m/k_{\max}(t)$. The pressure of the vacuum energy reads [9, 15]

$$\begin{aligned}p_{\text{vac}}(t) &= \frac{g}{6}\int_0^{k_{\max}(t)} \frac{d^3k}{(2\pi)^3}\frac{k^2}{\sqrt{k^2+m^2}} \\ &= \frac{1}{3}\frac{gk_{\max}^4(t)}{16\pi^2} h\left(\frac{m}{k_{\max(t)}}\right) \\ &= \frac{1}{3}\frac{gk_{\max}^4(t)}{16\pi^2}\left(1-\frac{m^2}{k_{\max}^2(t)}+\cdots\right),\end{aligned} \tag{21}$$

where $h(x)=\sqrt{1+x^2}(1-\frac{3}{2}x^2)+\frac{3}{2}x^4\ln(\frac{1}{x}+\frac{1}{x}\sqrt{1+x^2})$. It is clear from the expressions of Eq.(20) and Eq.(21) that the state equation of this vacuum energy is $p_{\text{vac}}(t)\simeq\frac{1}{3}\rho_{\text{vac}}(t)$ as long as $m\ll k_{\max}(t)$. At early times, $k_{\max}(t)$ was very large and the condition $m\ll k_{\max}(t)$ must be satisfied, this mean that this vacuum energy do not behave like a cosmological constant but rather like radiation, which is consistent with the fact that radiation was dominant in the early universe, and its energy density scales as $a(t)^{-4}$. When $k_{\max}(t)\le 2m_\nu$, the vacuum became stable, in order to make Theorem II hold, the condition $m\ll k_{\max}(t)\sim 2m_\nu$ must no longer be satisfied. Numerical analysis shows that the state equation of remaining vacuum energy begins to deviate from the behavior of radiation when $\frac{m}{2m_\nu}>0.1$, which gives a strong lower limit on the mass of the primordial field. In addition, if we assume that $m<m_\nu$, then the mass of the primordial field will be limited by $0.2m_\nu<m<m_\nu$, i. e. $0.1<\frac{m}{2m_\nu}<0.5$, so we get $f\left(\frac{m}{2m_\nu}\right)=1.08^{+0.13}_{-0.07}$. Of course, it is also possible if $m>m_\nu$, but it will not differ by two orders of magnitude from the neutrino mass, otherwise the theoretical limit on the upper limit of neutrino mass will be less than the experimental upper bound [16, 17].

(4). If the primordial field is a spin-1/2 field, it can be seen from the discussions in (3) that its mass is near the neutrino mass (or the difference is 1 to 2 orders of magnitude), then its property is similar to the sterile neutrino, which we call the sterile neutrino-like field. The reason why it is called sterile is that the cross section of the reaction process (8)(dark matter produces ordinary matter) must be very small, which is consistent with the fact that ordinary matter only accounts for a small part of the total matter. Therefore, there is a great possibility that dark matter is the residual vacuum energy of an sterile neutrino-like field(primordial field).

To summarize, the primordial field's vacuum energy, which behaves like a superfluid which flows without any viscosity rather than a kind of particle. This is the simplest explanation for dark matter. These arguments and Occam's razor lead us to the assumption that the relic of the primordial field which remains in the form of vacuum energy is the most likely candidate to be the main component of dark matter in the universe.

III. COMMENTS ON CONVENTIONAL DETECTION METHODS

If there exist remaining vacuum energy of the primordial field in the universe, its present energy density is

$$\rho_{\rm rvac}(t_0) = \rho_{cr} \times \Omega_{\rm DM} \\ = \frac{g k_{\rm max}^4(t_0)}{16\pi^2} f\left(\frac{m}{k_{\rm max}(t_0)}\right), \tag{22}$$

we set $\Omega_{\rm DM} = 0.26 \pm 0.01$ then approximately we get the present momentum cutoff is

$$k_{\rm max}(t_0) = 0.005^{+0.000}_{-0.000}\ {\rm eV}, \tag{23}$$

for primordial vector filed and primordial spin-1/2 filed, and

$$k_{\rm max}(t_0) = 0.006^{+0.001}_{-0.000}\ {\rm eV}, \tag{24}$$

for primordial scalar filed. Then the present maximum zero-point energy mode is $\frac{1}{2}k_{\rm max}(t_0) = 0.003^{+0.000}_{-0.000}$ eV(vector case and spin-1/2 case) or $\frac{1}{2}k_{\rm max}(t_0) = 0.003^{+0.001}_{-0.000}$ eV(scalar case). The mode number density of remaining vacuum energy is

$$n_{\rm vac}(t) = g\int_0^{k_{\rm max}(t)} \frac{d^3k}{(2\pi)^3} \\ = \frac{g k_{\rm max}^3(t)}{6\pi^2}, \tag{25}$$

so its present value is $n_{\rm vac}(t_0) = 6.34 \times 10^{-9}{\rm eV}^3 \simeq 825483\ {\rm cm}^{-3}$ for primordia vector field or $n_{\rm vac}(t_0) = 4.23 \times 10^{-9}{\rm eV}^3 \simeq 550756\ {\rm cm}^{-3}$ for primordial spin-1/2 field or $n_{\rm vac}(t_0) = 3.65 \times 10^{-9}{\rm eV}^3 \simeq 475238\ {\rm cm}^{-3}$ for primordial scalar field, which are much larger than the number density of CMB($n_\gamma \simeq 411{\rm cm}^{-3}$). Therefore we obtain the present averaged energy of each zero-point energy mode in remaining vacuum energy

$$\overline{\frac{1}{2}k} = \frac{\rho_{\rm rvac}(t_0)}{n_{\rm vac}(t_0)} \\ = \frac{\Omega_{\rm DM} \times \rho_{cr}}{n_{\rm vac}(t_0)} \\ = (1.72^{+0.07}_{-0.06}) \times 10^{-3}{\rm eV}, \tag{26}$$

if the primordial field is a vector field; and

$$\overline{\frac{1}{2}k} = \frac{\rho_{\rm rvac}(t_0)}{n_{\rm vac}(t_0)} \\ = \frac{\Omega_{\rm DM} \times \rho_{cr}}{n_{\rm vac}(t_0)} \\ = (2.58^{+0.10}_{-0.10}) \times 10^{-3}{\rm eV}, \tag{27}$$

if the primordial field is a spin-1/2 field; and

$$\overline{\frac{1}{2}k} = \frac{\rho_{\rm rvac}(t_0)}{n_{\rm vac}(t_0)} \\ = \frac{\Omega_{\rm DM} \times \rho_{cr}}{n_{\rm vac}(t_0)} \\ = (2.99^{+0.12}_{-0.11}) \times 10^{-3}{\rm eV}, \tag{28}$$

if the primordial field is a scalar field, which are about three to five times the averaged energy of photons in CMB, where we have set $\Omega_{\rm DM} = 0.26 \pm 0.01$.

A. Comments on conventional detection methods

Because the maximum energy of zero-point energy modes of the primordial field at present time and its mass are much smaller than a nuclei's mass, it is very difficult to detect them using the experiments which we have designed for detecting WIMPs by

recording the recoil energy of nuclei as it scatter off nuclei. And even since $\frac{1}{2}k_{\max}(t_0)/m_e \simeq 10^{-9}$, it is also very difficult to detect them by recording the electronic recoils as it scatter off an electron.

In the beginning, the standard model elementary particles are produced from vacuum state through Eq.(8), which are most likely irreversible processes, in this case, it is impossible to create the zero-point energy modes of the primordial field in a particle accelerator by the reverse processes of Eq.(8). However, it must be emphasized that each mode k of the primordial field as dark matter is in the lowest energy state $\frac{1}{2}\sqrt{k^2+m^2}$, while the energy of excited particles of the primordial field is $\sqrt{k^2+m^2}$. The process $e^+ + e^- \to k_1 + k_2$ can generate excited state particles(with energy $\sqrt{k^2+m^2}$) of the primordial field, but similar to process $e^+ + e^- \to \nu + \bar{\nu}$, its generation cross section must be very small, and k_1 and k_2 are not charged, and its mass is near the neutrino mass (or the difference is 1 to 2 orders of magnitude), so process $e^+ + e^- \to \nu + \bar{\nu}$ becomes the background of the process $e^+ + e^- \to k_1 + k_2$, which is difficult to distinguish experimentally, which is the difficulty of generating excited state particles of dark matter through particle accelerators.

For the conventional indirect detection, in some regions of the universe, such as the galactic center, where the remaining vacuum energy of the primordial field may accumulate. If its density become dense enough, the following annihilation processes have a probability to occur, just as it did in the beginning of the universe.

$$k_1 + k_2 \to \nu + \bar{\nu}, \tag{29}$$

$$k_1 + k_2 \to e^+ + e^-, \tag{30}$$

Based on previous discussions, neutrino and antineutrino has a probability to be produced in a region where if the remaining vacuum energy are accumulated up to $\rho_{\rm rvac} \geq \frac{g m_\nu^4}{\pi^2} f\left(\frac{m}{2m_\nu}\right)$, which is depend on the neutrino mass. The energy density condition for the process (30) to occur is much higher

$$\rho_{\rm rvac} \geq \frac{g m_e^4}{\pi^2} f\left(\frac{m}{2m_e}\right) \sim 10^{22}\ {\rm eV}^4 \sim 10^3\ {\rm g/cm}^3, \tag{31}$$

which is much larger than the density of iron. And nowadays, the averaged energy density of the remaining vacuum energy has decreased to $\rho_{\rm rvac} = \rho_{\rm DM} \simeq 0.26 \times 0.97 \times 10^{-29}\ {\rm g/cm}^3$, it is very difficult to be accumulated up to $10^3\ {\rm g/cm}^3$ again even in galactic center regions because of gravitational interaction. In Ref. [22], Gondolo and Silk derived a conservative estimate of dark matter density near the galactic center, they obtained $\rho_{\rm DM} \sim (1-\beta/3) \times 0.24\ {\rm GeV/cm}^3$ with $0 < \beta < 2$, so the process (30) mainly occurs only in the very early universe. Among all these indirect detections, theoretically the most viable method is to observe neutrinos result from the remaining vacuum energy modes annihilations in the dense regions of dark matter, such as the galactic center where if the remaining vacuum energy are accumulated up to $\rho_{\rm rvac} \geq \frac{g m_\nu^4}{\pi^2} f\left(\frac{m}{2m_\nu}\right)$, but it's a huge challenge in practice. I expect future neutrino telescope may confirm the nature of dark matter.

How to confirm the existence of the remaining energy of the universe's original energy in experiment is still an open problem.

IV. SUMMARY

In this article, I propose a new theory on the origin of dark matter abundance, in which I introduce a neutral primordial field, which is a new field beyond the standard model, its mass is limited to the vicinity of neutrino mass (or 1-2 orders of magnitude different from the neutrino mass). All the standard model elementary particles are produced spontaneously from this field in the Big Bang epoch of the universe and then these produced elementary particles decayed or annihilated in the well-known standard model interactions. The relic of the primordial field appears in a form of vacuum energy can not only give naturally the correct abundance of dark matter in the present universe, but provide a natural solution to the cosmological constant problem as well. The remaining vacuum energy of this primordial field is the most economical way among all the existing approaches to dark matter puzzle. We find that the conventional methods of detecting dark matter either fail or have great difficulties to detect the remaining vacuum energy of the primordial field, and how to confirm the existence of the remaining energy of the universe's original energy in experiment is still an open problem.

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APPENDIX

In the appendix, we give the reason for $T_1 > 0.1m_\nu$.
From the *Theorem II*, we have

$$\frac{gk_{\max}^4(t_1)}{16\pi^2} f\left(\frac{m}{2m_\nu}\right) a_1^3 = \frac{gk_{\max}^4(t_0)}{16\pi^2} f\left(\frac{m}{k_{\max}(t_0)}\right) a_0^3, \tag{32}$$

so the relation between $k_{\max}(t_1)$ and $k_{\max}(t_0)$ is

$$k_{\max}(t_1) = a_1^{-3/4} k_{\max}(t_0) \left[\frac{f\left(\frac{m}{k_{\max}(t_0)}\right)}{f\left(\frac{m}{2m_\nu}\right)}\right]^{\frac{1}{4}}, \tag{33}$$

where we have used $a_0 = 1$. Therefore from Eq. (33) and the relation formula $T_1 a_1 = T_0$, we obtain

$$\begin{aligned} \frac{T_1}{\frac{1}{2}k_{\max}(t_1)} &= \frac{\frac{T_0}{a_1}}{\frac{1}{2}k_{\max}(t_0) a_1^{-3/4} \left[\frac{f\left(\frac{m}{k_{\max}(t_0)}\right)}{f\left(\frac{m}{2m_\nu}\right)}\right]^{\frac{1}{4}}} \\ &= a_1^{-1/4} \frac{T_0}{\frac{1}{2}k_{\max}(t_0)} \left[\frac{f\left(\frac{m}{2m_\nu}\right)}{f\left(\frac{m}{k_{\max}(t_0)}\right)}\right]^{\frac{1}{4}}. \end{aligned} \tag{34}$$

Eq. (23) and Eq. (24) gives $\frac{1}{2}k_{\max}(t_0) \simeq 0.003$ eV. Numerical analysis shows that the value of $\left[\frac{f\left(\frac{m}{2m_\nu}\right)}{f\left(\frac{m}{k_{\max}(t_0)}\right)}\right]^{\frac{1}{4}}$ is approximately equal to 1, and substituting the values $T_0 = 2.348 \times 10^{-4}$ eV, $\frac{1}{2}k_{\max}(t_0) \simeq 0.003$ eV and $\frac{1}{2}k_{\max}(t_1) = m_\nu$ into Eq. (34), we obtain

$$T_1 \simeq \frac{1}{a_1^4} \times (0.1m_\nu). \tag{35}$$

Since $0 < a_1 < 1$, we get approximately $T_1 > 0.1m_\nu$.

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